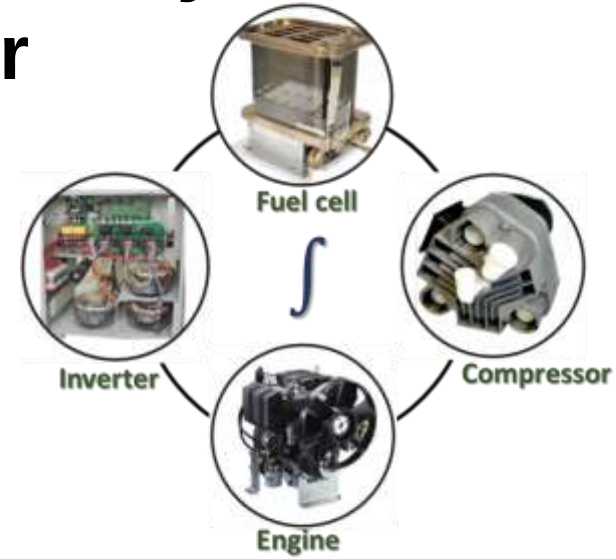
High Efficiency, Low Cost & Robust Hybrid SOFC/IC Engine Power Generator

Rob Braun, Colorado School of Mines



Project Vision

- Demonstrate a hybrid fuel cell system that can drive both radically lower cost (<850 $/kW) and ultra-high efficiency (>71%) for 125 kW class distributed power generation applications.

- Integrates lower-temperature, pressurized metal-supported SOFC technology (¼ - ½ scale) with full-scale IC engine, positive displacement BOP, and novel power-conditioning technology.

Project Overview

Fed. funding:	$3.1M
Length	24 mo.

Team member	Location	Role in project
Mines	Golden, CO	**Lead**, Systems/Control, SOFC stack, TEA, T2M
Colo State Univ	Ft. Collins, CO	Tail-gas engine, Integration test facility
Kohler Power Systems	Kohler, WI	Engine, Alternator, High efficiency/Low-cost inverter, T2M, **Commercialization partner**
Air Squared	Broomfield, CO	Scroll Compressor/Expander

Context/History of project

Mines: >20-yr experience on fuel cell systems and SOFC technology.
: **REBELS** and **REFUEL** projects

CSU : **ARID** project; long history in alt. fuels and stationary engines

Kohler: Commercial/Industrial engine power systems from 20 kW to 40 MW

Air Squared: World leader in scroll tech, >50 govt projects, **GENSETS**

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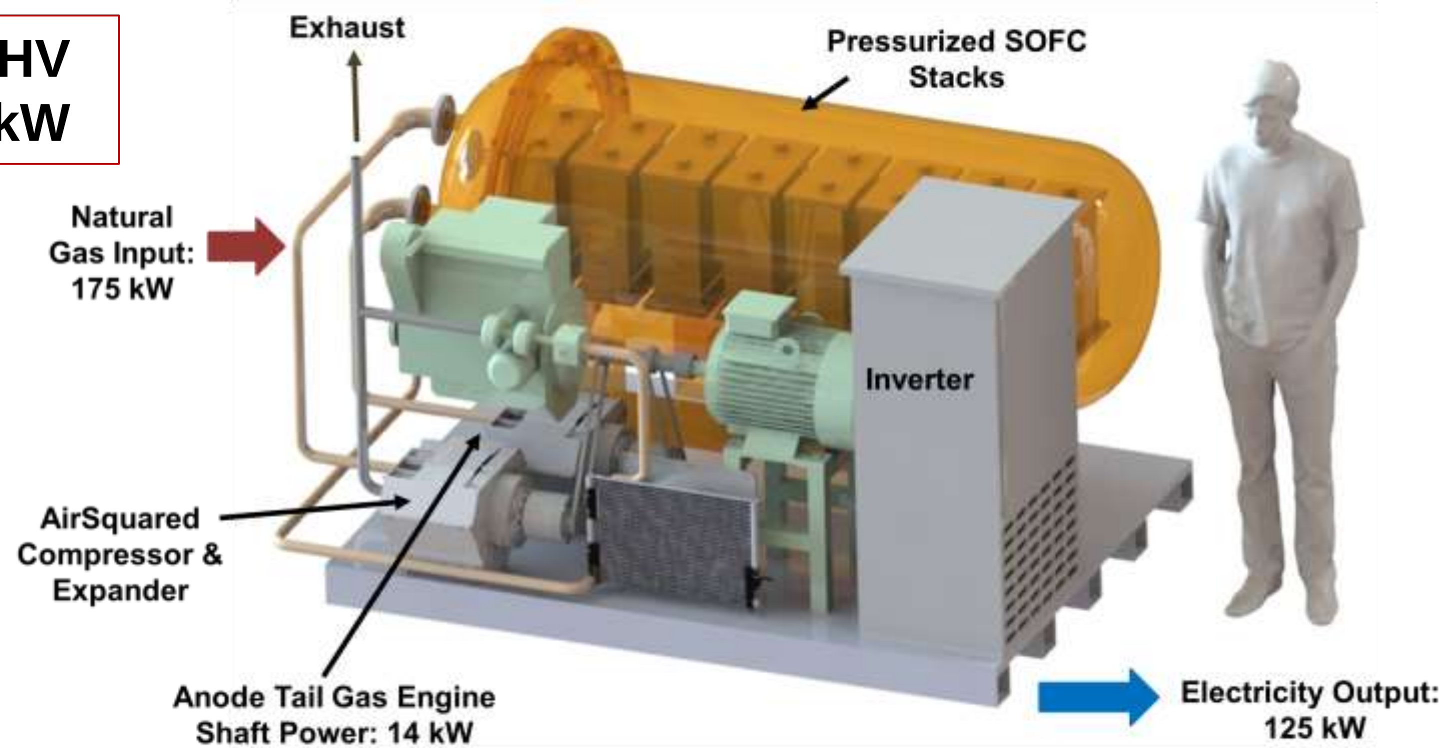
Innovation - Integrate robust, pressurized metal-supported SOFC with high η engine, inverter and rotating equipment

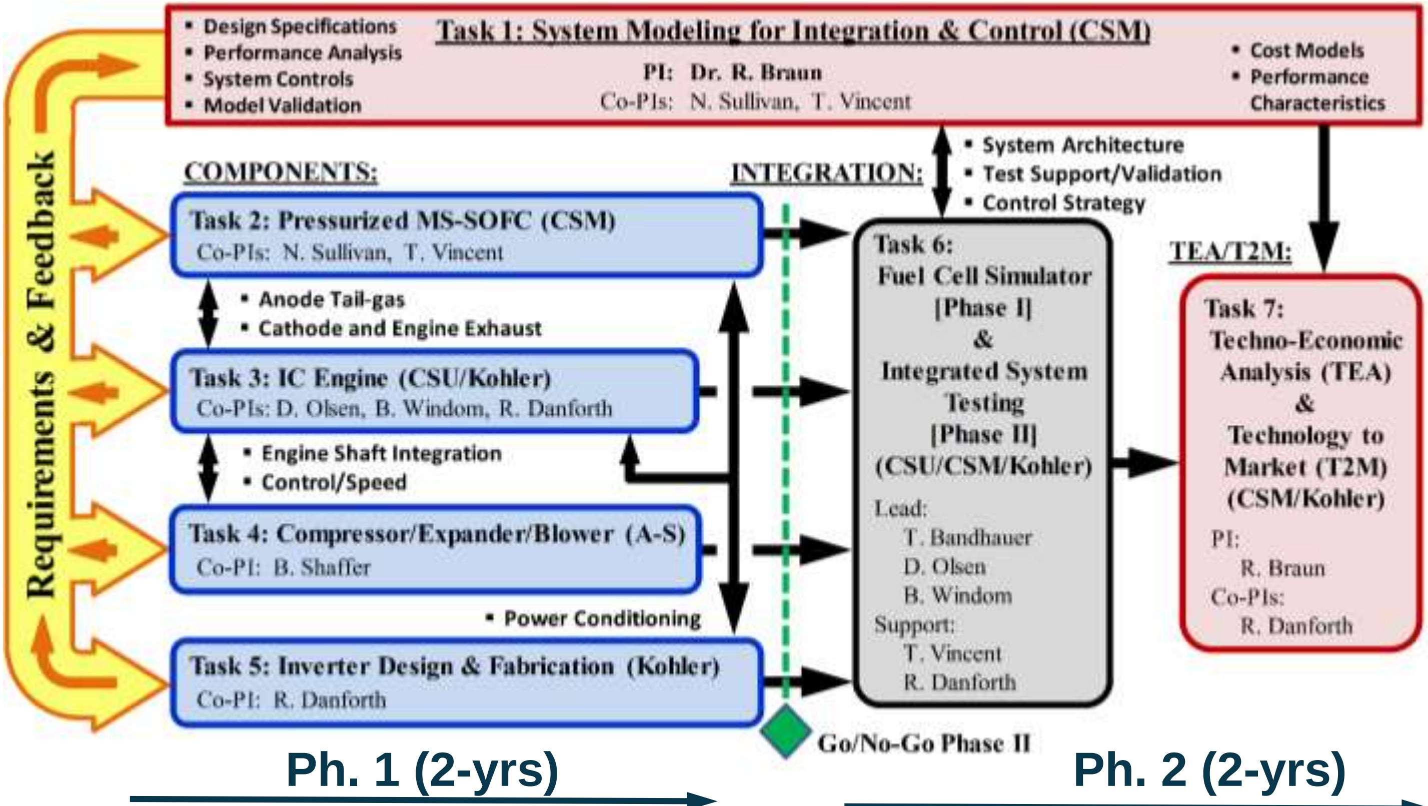
>71% LHV
<850 $/kW



Features:

- Low cell temp, thermal management → reduce air preheater duty by >60%
- Pressurization → increases power density, lowers both costs and BOP duty
- Gasified diesel engine converts residual fuel gas to drive auxiliaries (BOP)
- Simple after-treatment enables low engine emissions (NOx, CO)

Technical Objectives & Organization

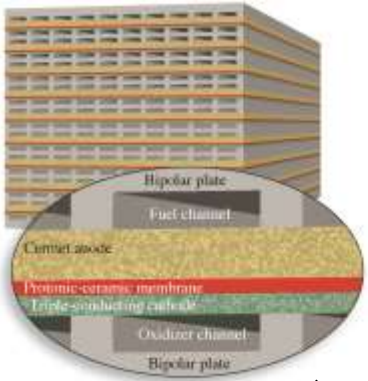


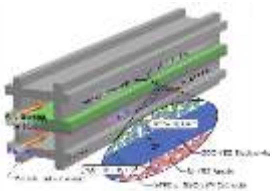
Outline

- System Modeling for Integration
- Pressurized Stack Activities
- Anode Tail-gas Engine & Inverter Development
- T2M & Risks

Multi-scale modeling moves from physical models to process systems design & control to TEA

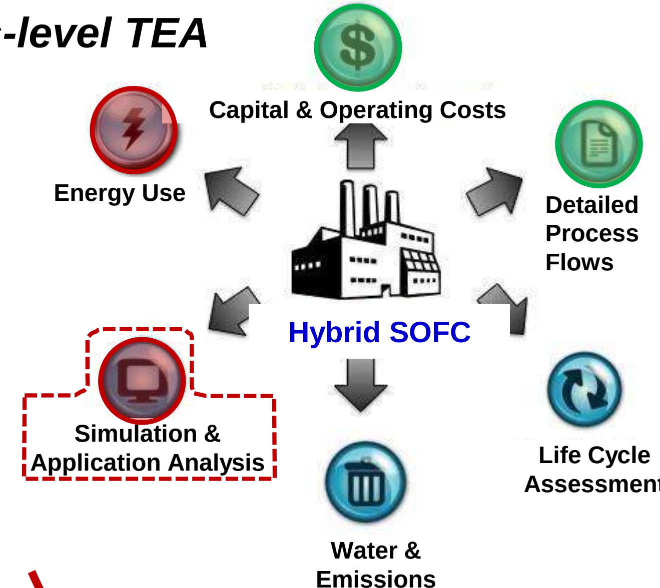
Stack Modeling



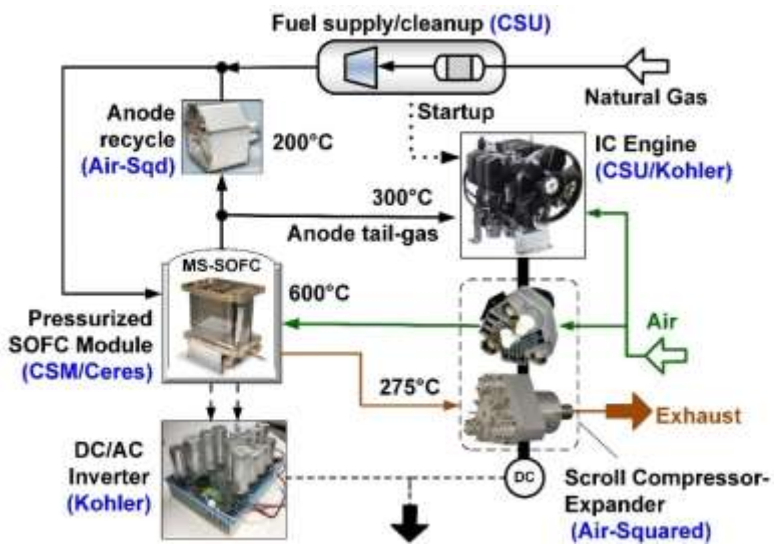


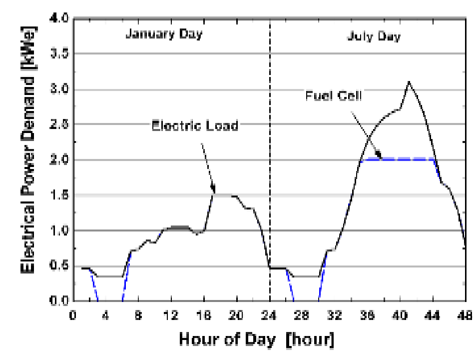
Cell Modeling

Systems-level TEA



Process System Design & Control





Simulation & Application Analysis

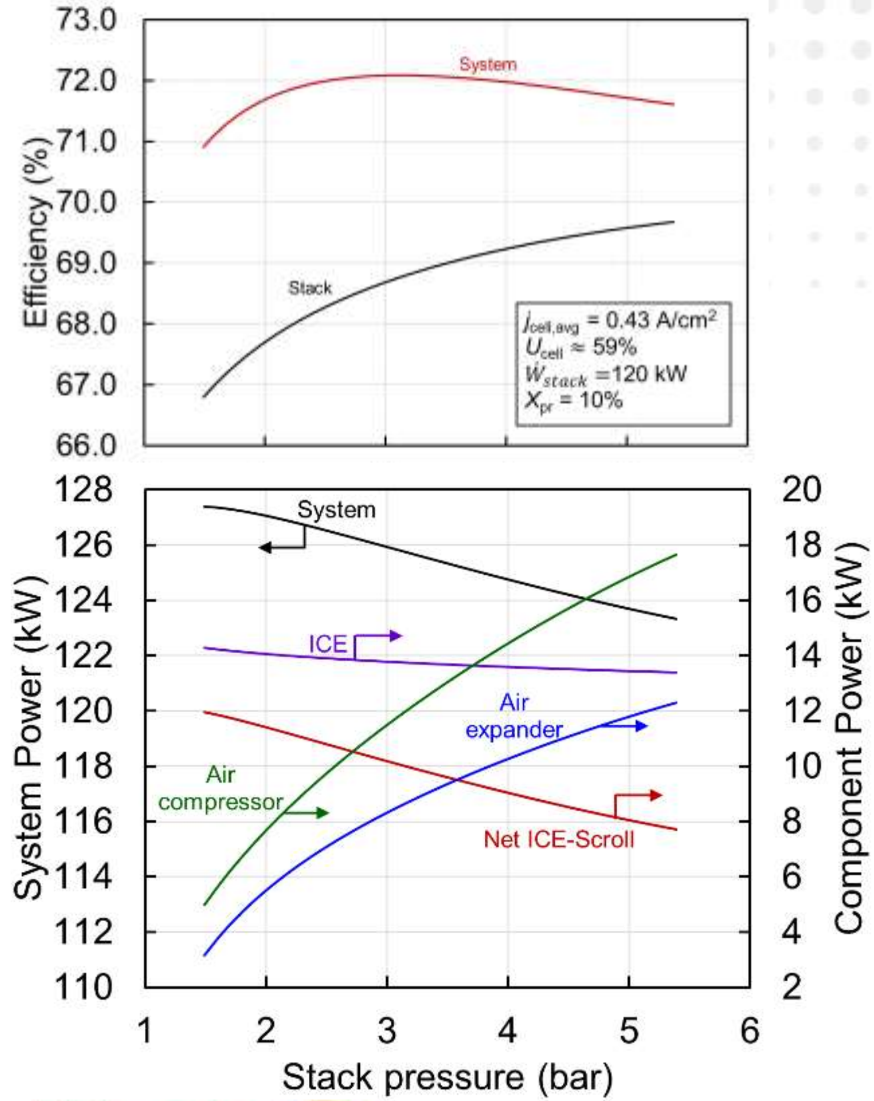
System-level Trade Studies: Optimal efficiency represents a balance between stack and BOP

- Stack efficiency increases with pressure due to lower ASR

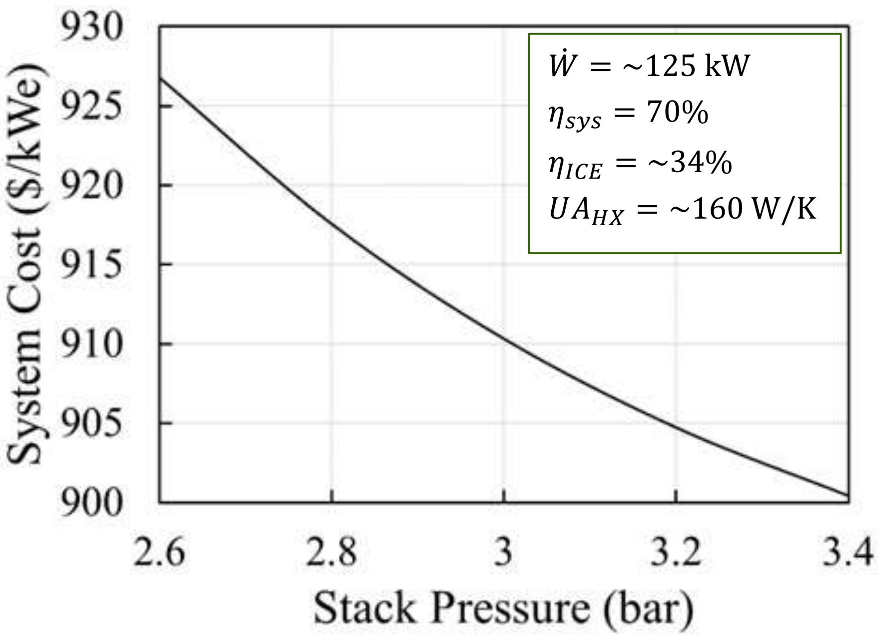
- System efficiency peaks ~3 bar
  - Balance between stack performance and BOP parasitics
  - Air compressor power increases faster than air expander power

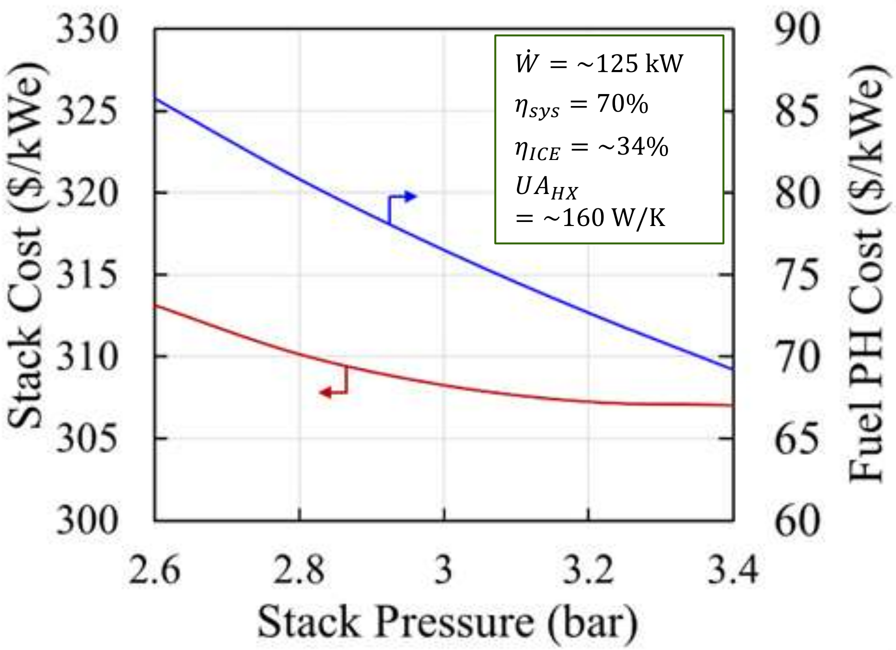
Notes:

- Rotating machinery efficiency is not sensitive to pressure in this study



Stack thermal management is critical to achieving high power density, low cost system designs



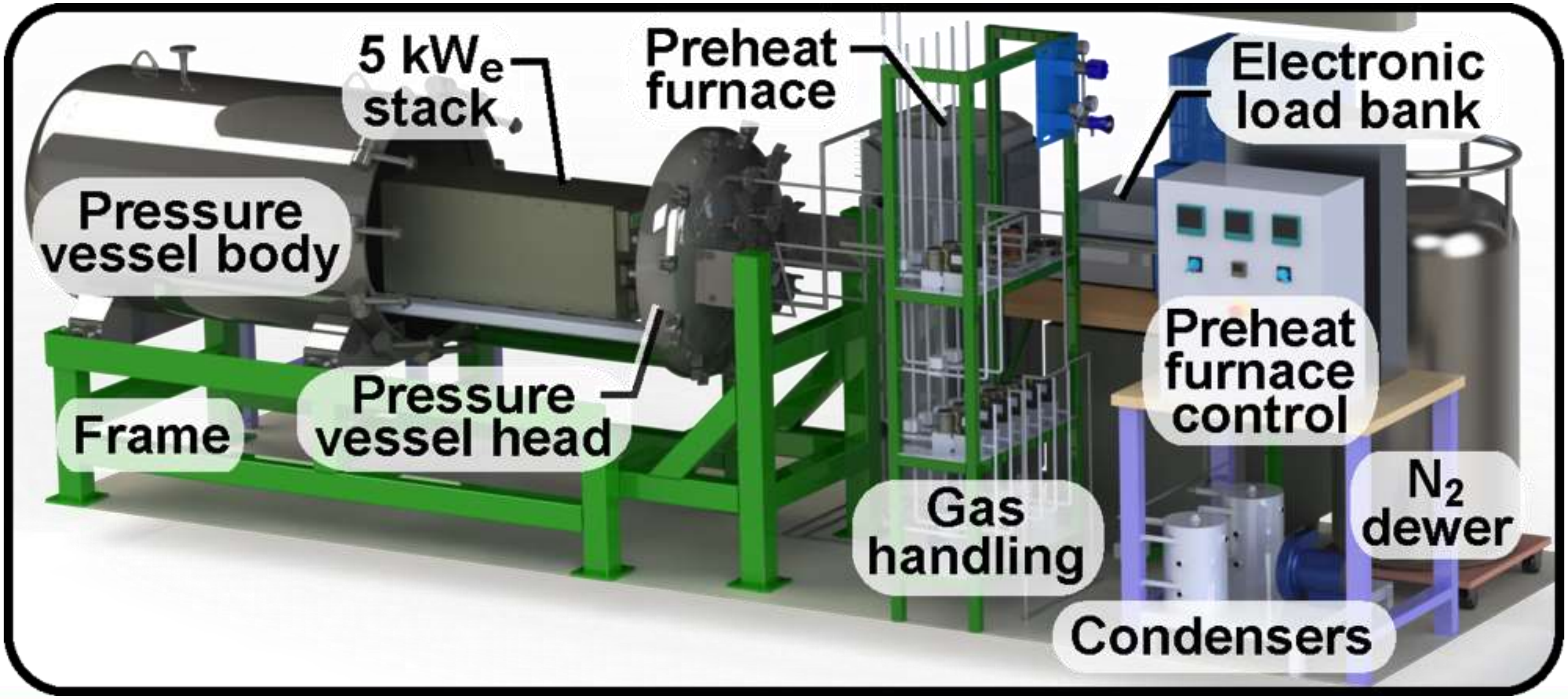


- **Critical system design constraints involve:**
  - Avoiding carbon deposition and expander inlet temperature limits,
  - Staying within stack thermal limits (both ΔT and max T_{PEN})
  - Trade-off between high current density design and stack degradation (O&M)
- **Heat exchanger performance and cost expectations are also crucial**

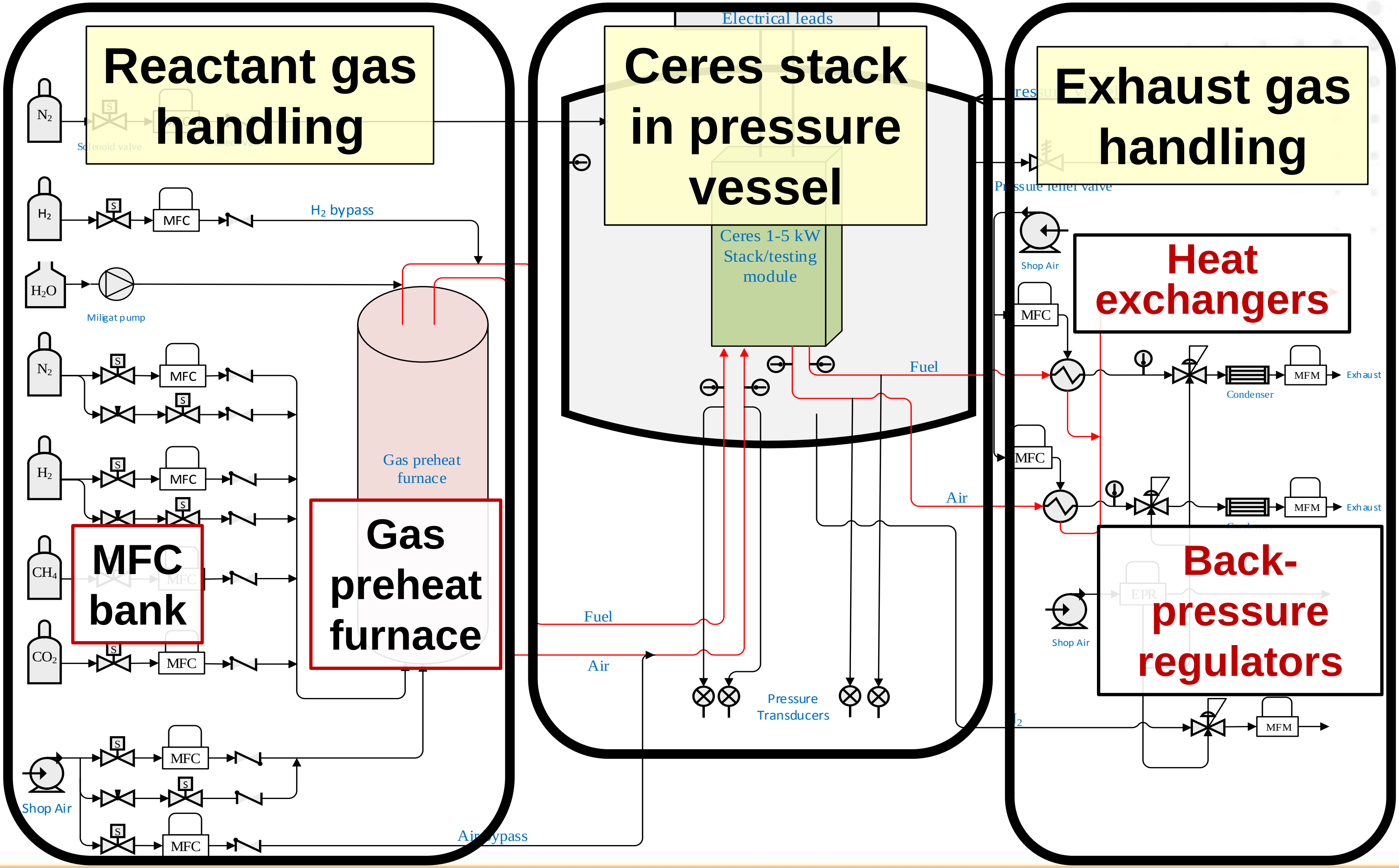
Mines has built a unique test stand to characterize SOFC stack performance at pressure

Objectives

- Explore SOFC stack performance at up to 5-bar$_g$ pressure
  - Extent of fuel pre-reforming, fuel utilization, and electric current
- Create data sets for calibration & validation of system models



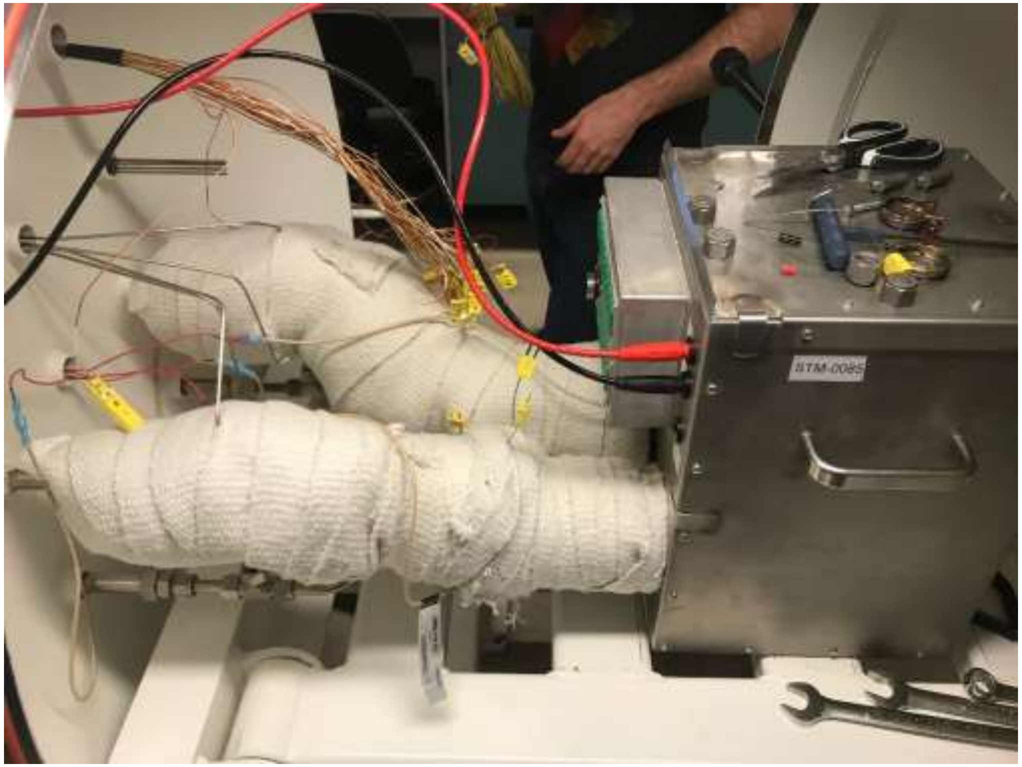
The pressurized stack test stand is comprised of three primary subassemblies



The pressurized stack test stand is comprised of three primary subassemblies

V4 Ceres Power 1-kW stack test module is installed as shown and facility enables ready swap out

- Pressurized testing initiated
- First successful results at 4-bar

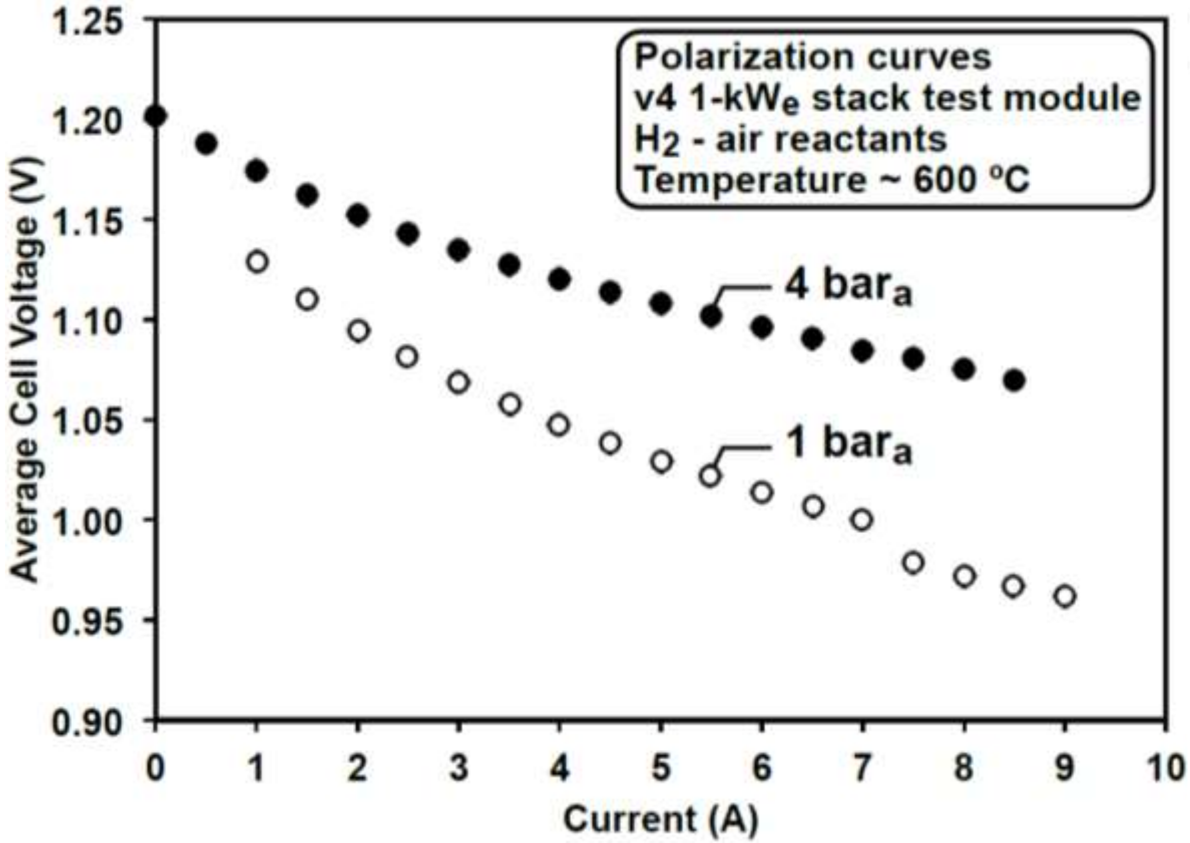


The pressurized stack test stand is now online, with electrochemical performance tests ongoing

1-kWe pressurized stack testing now underway (H_2/N_2 and air)

- First round of test results support theoretical performance predictions for pressurization effect on voltage increase

- **90-100mV boost due to pressurization**
- **Ceres 5-kWe stack to be delivered to Mines in late Fall 2019**

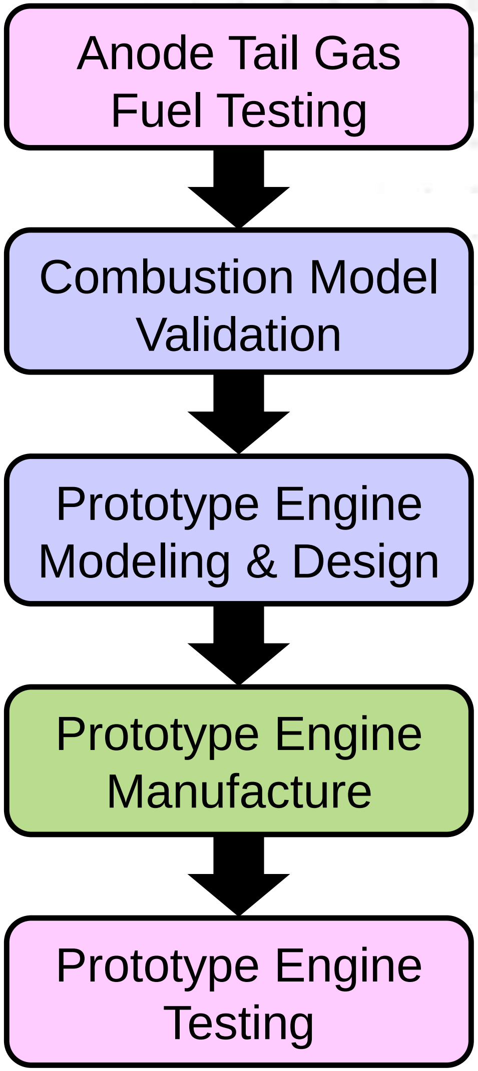


High Efficiency Tail Gas Engine Development Pathway

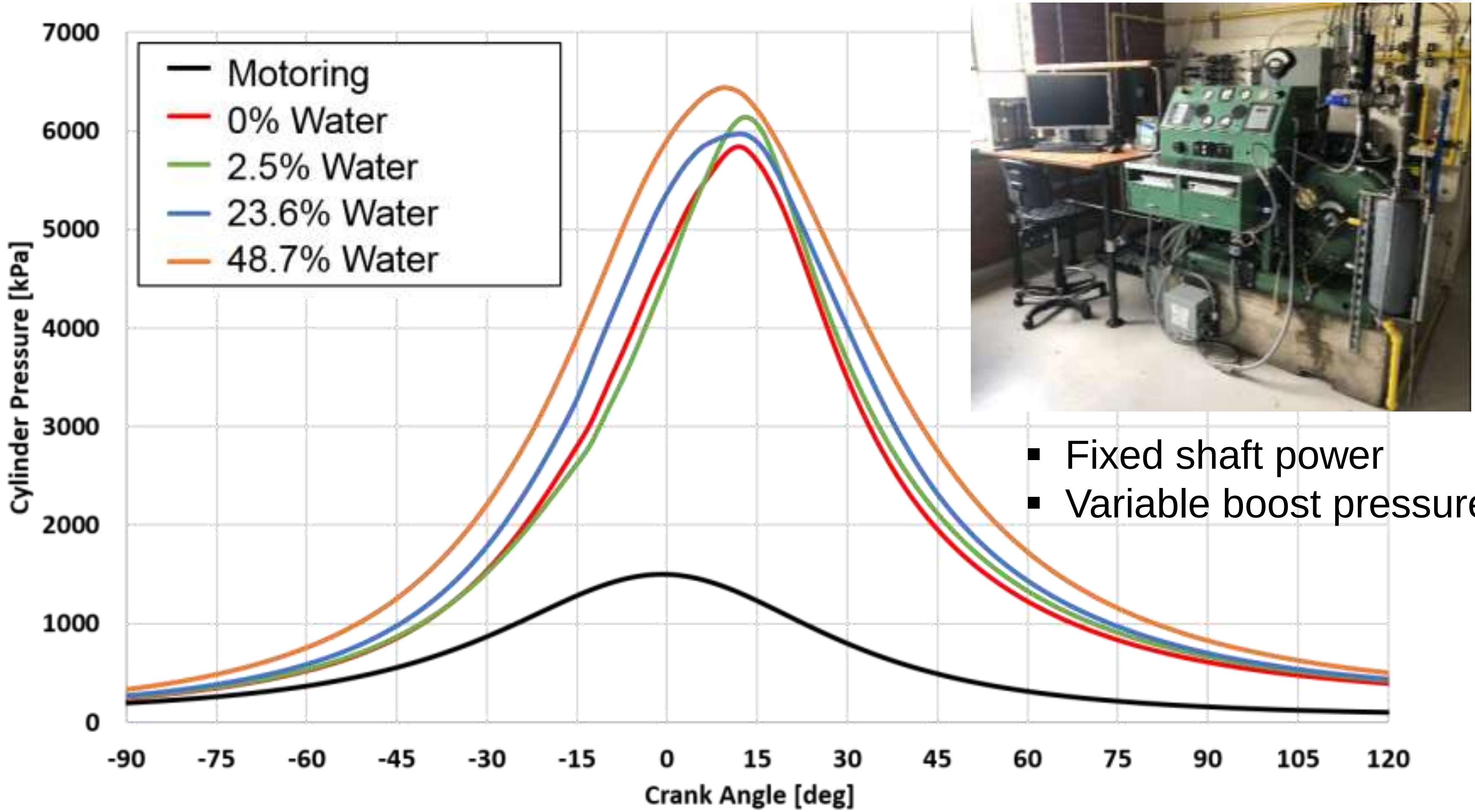
Goals:

1. **Develop high efficiency anode tail gas engine**
   - Characterize fuel burn characteristics
   - Validate combustion model
   - Determine engine operating envelope
   - Design & manufacture engine

2. **Test prototype engine with simulated anode tail gas**
   - Construct fuel cell simulation facility
   - Install and test engine in facility
   - Verify engine performance targets



CFR Testing – All Fuel Blends Successfully Burned



- Fixed shaft power
- Variable boost pressure

Testing done for anode tail gas over range of water concentrations

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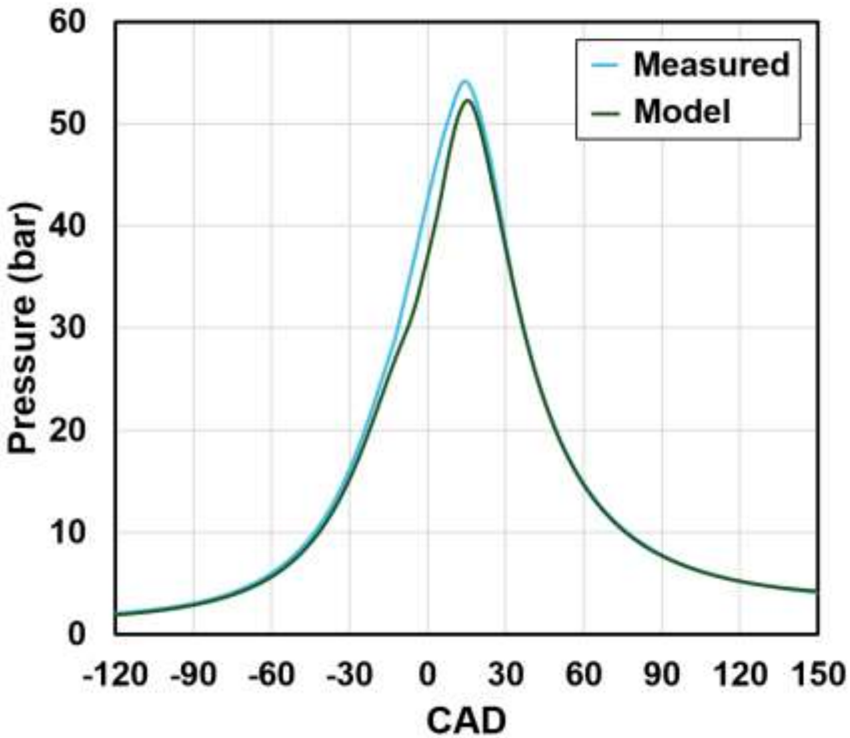
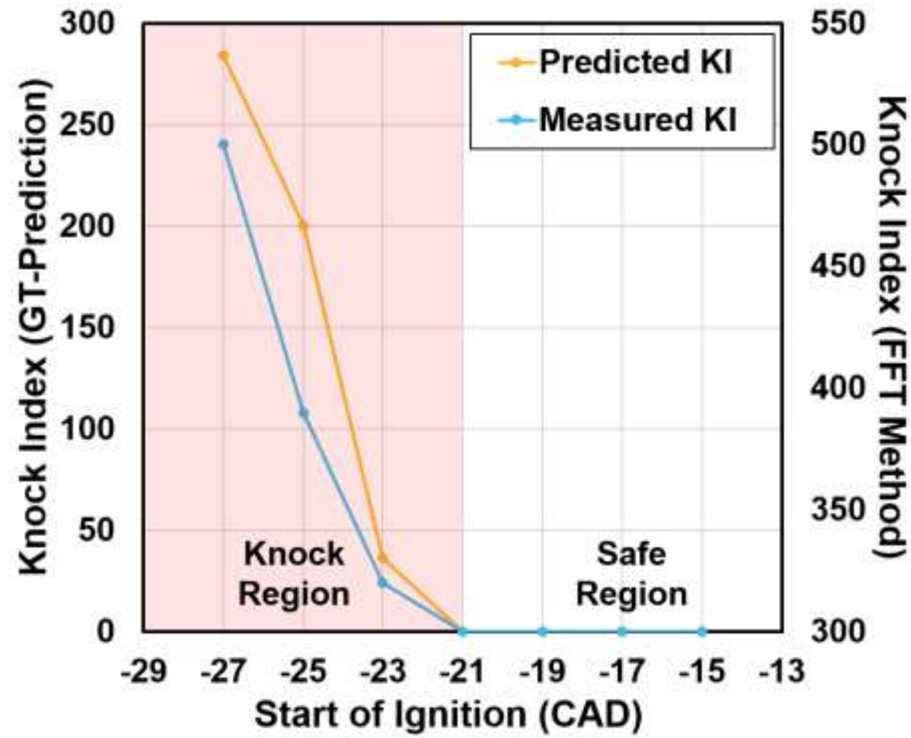
GT Power combustion model calibrated with CFR experimental data and then verified

Power and fuel-air charge



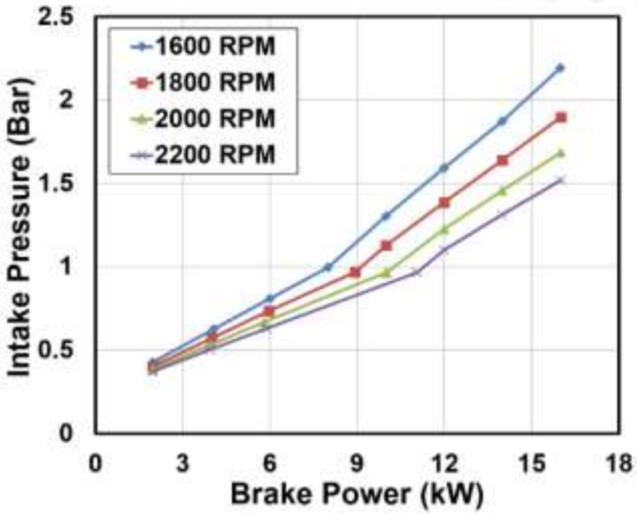
End-gas chemistry

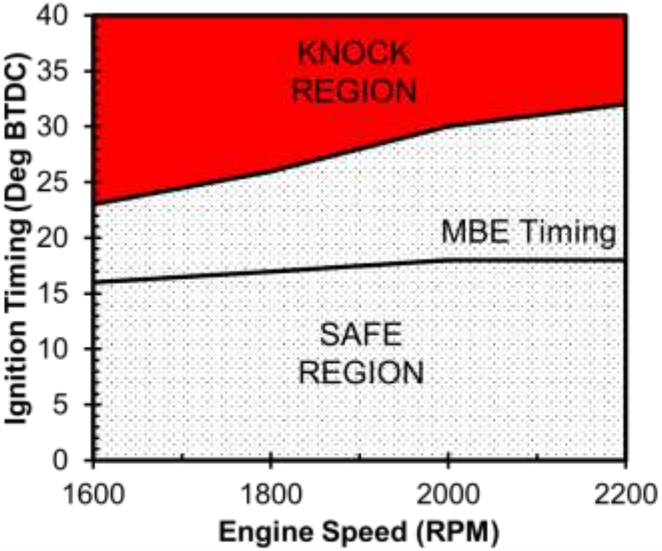


Calibrated 2-zone combustion model used to accurately predict engine performance while operating with anode tail gas

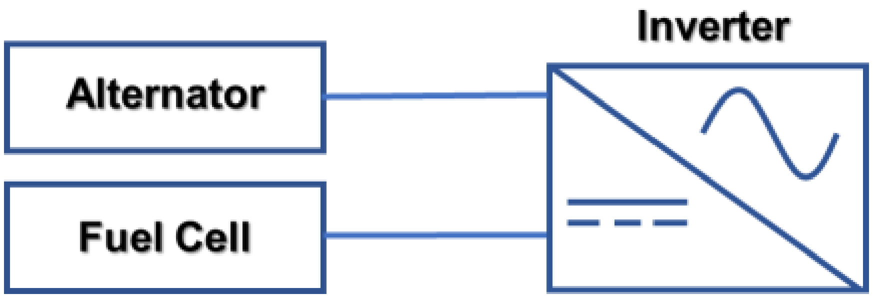
Prototype Engine Modeling – Engine Operating Envelope

- Validated combustion models used in GT-Power to simulate gasified Kohler diesel engine to establish envelope
- **Operating specifications**: valve timing, boost pressure, speed, spark timing,…
- <u>Next step:</u> Engine installed in test facility





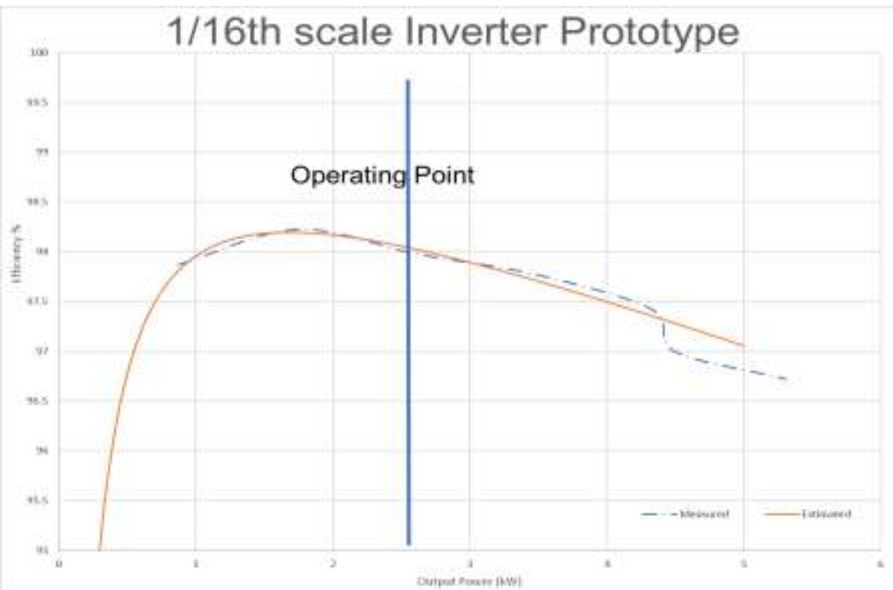
Inverter development targets 98% efficiency at low capital cost



Inverter Design Targets

- 480VAC 3-Phase Output
- 98% Efficiency at 120kW (150Amps)
- Power Factor Correction up to 0.8pf
- 20 Year Design Life
- Grid Tied with Internal Protection
- Island Operation

Performance



Enabling Technologies:

SiC wide-bandgap switches

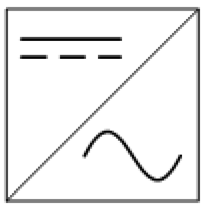
- Lower conduction & switching losses
- Higher speed switching, smaller output filter; transformer-less operation

Amorphous Iron Cores

- Lower cores losses, High saturation levels allow compact design
- Compactness reduces winding losses

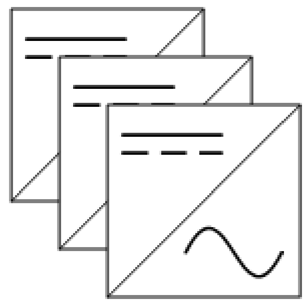
Phase 1 inverter activites are focused on sub-scale demonstration at low (~2 kW) and medium (15 kW) power

Phase 1



Input: 440VDC
Output: 277VAC
Power: 2.5kW
Losses: ~60W
Heat Sink: 250W
Target Efficiency: 98%

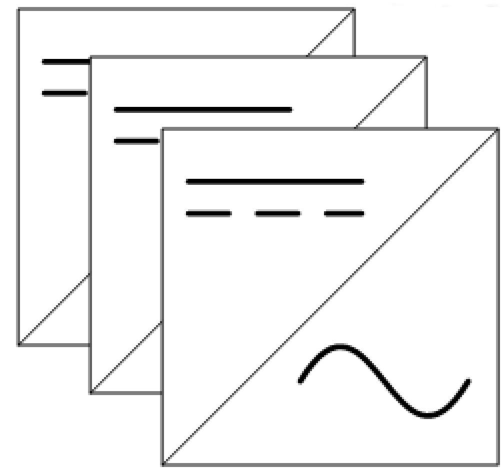
Complete



Input: 3 X 440VDC
Output: 3 X 277VAC (480V)
Power: 3 X 5kW (15kW)
Losses: 3 X ~160W
Heat Sink: 3 X 250W
Target Efficiency: 97%

In-Process

Phase 2



Input: 3 X 440VDC
Output: 3 X 277VAC (480V)
Power: 3 X 42kW (125kW)
Losses: 3 X ~800W
Heat Sink: 3 X 1kW
Efficiency: 98.0%

Market analysis provides some insight into current customer motivations

Data Centers

Anticipated First Markets

- Critical loads
- Commercial buildings

Commercial Buildings

Approach to Market

- Customer interviews completed
- LCOE primary reason for adoption
- Environmental was secondary **('green' perception matters)**
- Strong preference for PPA to reduce CAPEX & Risk
- Built-in UPS (Storage) has potential to improve ROI - Systems Approach

Risks

SYSTEM-LEVEL
- Control:
  - over dynamic operating range
  - through mode transitions
- SOFC/Engine interactions → Test facility
- Heat exchangers (type, cost, performance)

COMMERCIALIZATION
- Emissions concerns → Bloom
- Spark spread variation
  - Hybrid RE/DG may help

COMPONENTS

SOFC Stack
- Performance (>350 mW/cm^2) → multiple pathways identified
- Durability (degradation, coking…)
- Cost trajectory

Engine
- Durability/service intervals for target life cycle (20,000-h) → low rpms, durable diesel
- Combustion control with low-Btu/high moisture content fuel → ECU with sensors
- 35%-LHV engine efficiency target → lower friction, alt. engine platform, high effic. TC
- Fuel flexibility during startup operations → throttle engine, advance timing

The Team

Rob Braun, Mechanical Engineering
Neal Sullivan, Mechanical Engineering
Tyrone Vincent, Electrical Engineering



KOHLER POWER SYSTEMS

Rob Danforth, Director – Engineering Labs
Isaac Frampton, Staff Engineer

Colorado State University

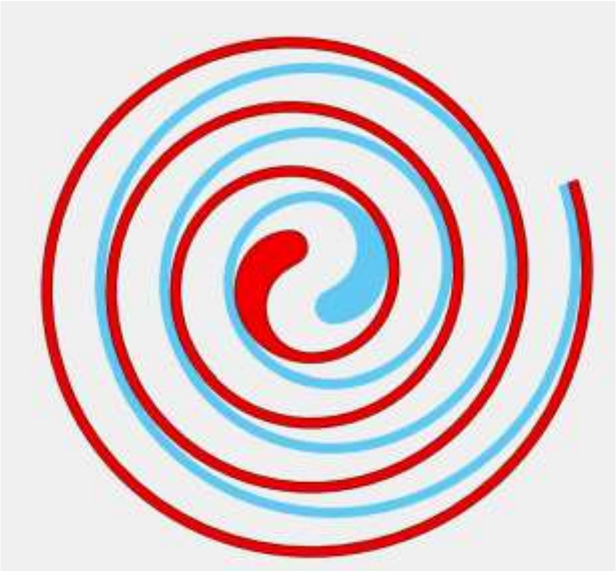
Todd Bandhauer, Mechanical Engineering
Dan Olsen, Mechanical Engineering
Brett Windom, Mechanical Engineering

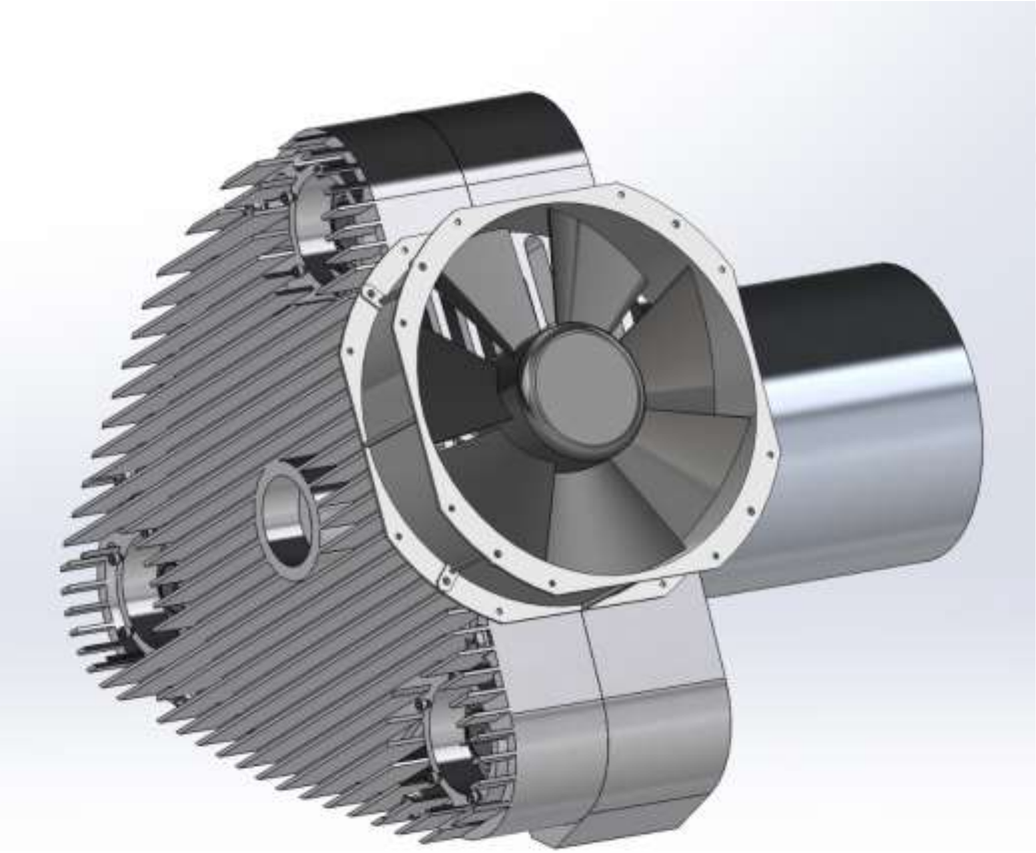

air squared

Bryce Shaffer

Compressor Concept

- Speed: 2200 RPM
- P_in: 1.013 Bara
- P_out: 3.5 Bara
- SV: 1803 cc
- VR: 2.41





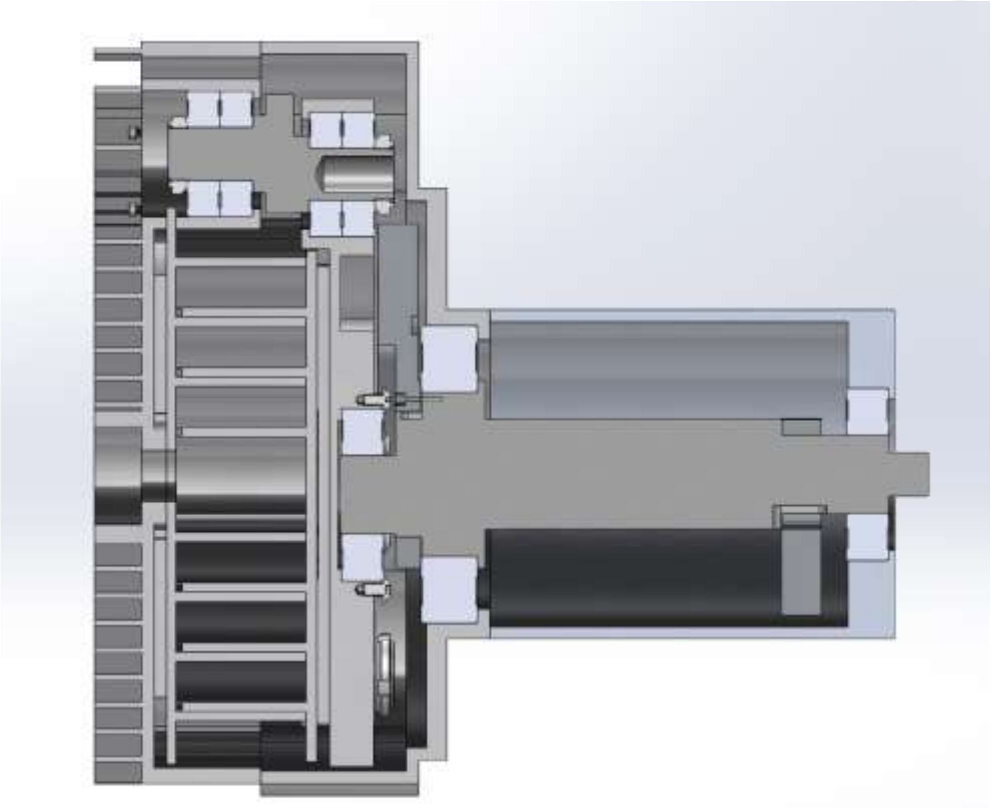
Compressor Design Features

Design Features

- Enclosed scroll geometry
- Fan Cooling
- Independent drive
- Idler bearing design
- Idler bearing isolation
- Designed to be cast

Design Concerns

- Overall size, machinability
- Bearing cooling



Engine Delivery & Fuel Cell Simulator Construction

- Gasified diesel engine delivered to CSU
- Test cell preparation on-going
- Anticipated start-up: Mid October

Test cell fabrication on schedule